**Fate of a Martian impact crater**

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**Abstract**

Ancient Martian impact craters on Mars offer a window into planetary-scale geological events, and hence, they serve as proxies for studying global processes like colossal volcanism and fluvial activity. Among these craters, the 76.97 km Morella complex crater stands out as a remarkable feature, demonstrating the intricate geological history. Despite its sepulchring, it hosts Ganges Cavus, a significant collapse structure, and Elaver Vallis, an outflow channel from the breached eastern rim. A four-stage narrative explains the crater's odyssey from inception to its current state, exhibiting diverse planetary processes that shape the fate of Martian impact craters. The transient morphology reveals a diameter of 64.65 km, rim height of 2.86 km, depth of 2.07 km, and central peak of 0.57 km, formed between Ga and Ga. The preponderance of pyroxene and olivine in the Morella plains indicates volcanic activity, likely triggered by the impact. The heat source from Ophir Catenae Structural Complex might have ruptured the cryosphere, resulting in the formation of Ganges Cavus and eventual filling of the crater, which ultimately breached and formed Elaver Vallis around Ga. The modelled flood reveals a volume of 2.7 × 1012 m3, and an estimated peak velocity of 8.98 × 107 m3/s. This crater also witnessed another fluvial activity that resulted in the formation of the dark toned channel of Ga. This extensive range of geomorphic and geological processes positions Morella Crater as a promising location for future Mars missions.

*Keywords:* Morella Crater, Ganges Cavus, Elaver Vallis, catastrophic flooding, Mars

**Plain language summary**

Ancient impact craters on Mars depict an array of geological and geomorphological processes, which decides the destiny from a pristine to a highly denuded crater. Thus, Morella, a late Noachian aged complex crater, represents an ideal candidate for demonstrating the multitude of processes that acted on the Martian terrain. Over time, Morella Crater has experienced various processes, such as aeolian, volcanic activity, mass movements, flooding, and breaching. This crater hosts an extremely deep collapse structure, known as the Ganges Cavus, and an outflow channel, named Elaver Vallis. The study outlines a four-stage process detailing the odyssey of Morella Crater, many of which exemplify the global planetary processes like volcanism, subsidence, flooding, outflow channel formation and impact events. This extensive range of geomorphic and geological processes positions the Morella crater as a promising location for future Mars missions.

**Key points**

1. Ancient impact craters on Mars seem potential for studying planet-scale geological processes.
2. Morella Crater houses collapse structure, outflow channel indicating diverse geological processes like tectonism, volcanism, and flooding.
3. Crater size-frequency distribution suggests an age of ~ 3.0 Ga for the Elaver Vallis through a flood water release of 2.7×1012 m3.

**1 Introduction**

The Martian terrain is etched with scores of impact craters, which hold the key to unravel the plenitude of cosmic history as impact cratering is one of the most fundamental geological processes of the Solar System (cf. Shoemaker, 1983; Melosh, 1989). Although impact craters are common on rocky planetary bodies, the Martian craters exhibit unique characteristics, especially relative to terrestrial (Earth) and Lunar counterparts. Earth is a planet with active plate tectonics (Valencia et al., 2007), meanwhile, Moon is tectonically inactive (Marvin, 1986). In contrast, Mars depicts an intermediate tectonic scenario, wherein it was tectonically active in the geological past (Sleep, 1994). The tectonic evolution of the planets has a marked effect on the associated number of impact craters. Mars' topography, when compared to Earth's terrain, is much more crater-dominant (Robbins and Hynek, 2012), but with degradation at different rates and intensity.

The importance of impact craters on planetary bodies can be testified by the crater size-frequency distribution (CSFD), as it was used for discerning the age of planetary surfaces (Barlow, 1988). Based on CSFD, the Martian terrain is classified as Noachian (4.6 to 3.7 Ga), Hesperian (3.7-3 Ga), and Amazonian (3 Ga to present) (Neukum and Hiller, 1975). Approximately 40% of the Martian surface is linked to Noachian period, covering a period from the solidification of Mars’ crust up to ca. 3.7 Ga (Hartmann and Neukum, 2001). Hesperian-aged units (3.7–3.0 Ga) cover ~34% of the Martian surface area, and the remaining ~26% is dated as Amazonian (3.0 Ga to present) (Barlow, 2010). Furthermore, Scott and Carr (1978) divided the Martian periods into epochs: (i) early, middle, and late Noachian, (ii) early and late Hesperian, and (iii) early, middle, and late Amazonian. Apart from the ages, the distribution of craters across the Martian terrain also depends on the distinctive dichotomy between the northern lowland **(**0-3 km below the mean Martian geoid) predominated by low-lying areas and vast plains indicative of an ancient ocean, and southern highlands (1-5 km above the mean Martian geoid) dominated by elevated terrain and an extensive volcanic system (Golombek and Phillips, 2010). The northern plains are topographically lower and contain a fewer craters than the rugged and heavily cratered southern highlands (Tanaka et al., 2014). As a result, craters are not evenly distributed on Mars; instead, they are distributed in select regions, but with a substantial number of large craters (Barlow, 2010).

Impact cratering process has been active since the early formation of Mars, therefore, all the geomorphic and geologic processes this planet has witnessed like the formation of valley networks (Baker et al., 1992) volcanism (Rani et al., 2021), formation of collapse structures (Rodríguez et al., 2005), tectonic deformation (Ruj et al., 2019), sedimentary deposition (Fassett and Head, 2005), formation of outflow channels (Rodriguez et al., 2015), delta formation (Hauber et al., 2013), and so on must have manifested in craters because craters as large as 3300 km diameter (Utopia) and 2300 km diameter (Hellas Planitia) were formed during the early history of Mars (Searls et al., 2006). Understanding and classifying the intensity of these events on a planetary scale seems difficult and hence, we consider craters as proxies to understand the above processes and to place them stratigraphically.

***1.1 Synopsis of Martian history***

Noachian period marks the earliest geological events shaping Mars and defining its fundamental surface features. The ancient highlands formed during early Noachian period make up a substantial portion of Mars' southern hemisphere (Nimmo and Tanaka, 2005). These regions consist of heavily cratered terrains, indicating a prolonged period of late heavy bombardment (LHB) (Barlow, 2010). The presence of valley networks in these highlands suggests the influence of fluvial activity and the subsequent formation of phyllosilicates (Fairén et al., 2010; Singh et al., 2016; Paramanick et al., 2021). Although precipitation is noted across Noachian, the late Noachian is associated with comparatively more precipitation than previous periods on Mars' history (Craddock and Howard, 2002). The earliest Martian crust includes materials from the early Noachian, concealing evidence of older impact craters and volcanic activity (Cabrol and Grin, 1999; Vijayan and Mangold, 2021). The Noachian geological units usually depict spectral signatures suggesting a significant presence of rocks with basaltic compositions, wherein during early and middle Noachian low-Ca pyroxene (LCP) rocks were prevalent, and rocks characterized by high-Ca pyroxene (HCP) remained dominant from late Noachian to Amazonian (Viviano et al., 2023). One of the notable features of middle Noachian is the continued formation of impact craters making it a dominant geological process (Irwin III et al., 2013). The presence of fluvial features, such as impact crater lakes was prominent during this period (Cabrol and Grin, 1999). At the same time, early crustal activity and tectonic evolution were recorded around 3.8 Ga and 3.5–3.6 Ga, respectively (Ruj et al., 2019; Rani et al., 2021). During late Noachian, the cratered highlands underwent further modification through volcanic, sedimentary, and impact-cratering processes (Fassett and Head III, 2005). During this period, sedimentary deposits, provides evidence favouring ancient fluvial and lacustrine environments, were formed (Fassett and Head III, 2005). Thus, the Noachian period is fundamental for deciphering the planet's earliest geological evolution, its potential for hosting life and factors relevant to shaping its current surface and atmosphere but the Noachian craters display greater signs of degradation.

Hesperian period on Mars encompassed a wider array of geological processes when compared to Noachian period. Early Hesperian period witnessed significant geological erosion, including widespread collapse structures, catastrophic floods, formation of outflow channels (Rodriguez et al., 2015), and the transformation of Noachian highlands into chaotic terrains (Sharp, 1973). This period was also characterized by the formation of delta (Hauber et al., 2013), and the presence of glacial activity (Head and Pratt, 2001). Late Hesperian is marked by extensive volcanic and tectonic activities (McGill and Dimitriou, 1990).

The transition from Hesperian to Amazonian displayed a combination of fluvial, volcanic, glacial, and aeolian deposits. Amazonian period on Mars represents a relatively quiescent phase of geological evolution. During this period, the planet experienced relatively fewer instances of volcanism, impact cratering, and tectonic activity. Early Amazonian period on Mars is characterized by smooth crater floors (Morgan and Head III, 2009) and the presence of rayed craters (McEwen et al., 2005). Middle Amazonian is dominated by morphologically fresh pedestal craters (Kadish et al., 2010). The present-day geological and geomorphic state of Mars is the late Amazonian. The formation of concentric crater fill (Levy et al., 2010), lobate debris aprons (Berman et al., 2015), and lineated valley fill (Kress et al., 2008) dominated the late Amazonian. Hence, the Amazonian period is the most recent chapter in the planet's geological history. A synopsis of the entire geological processes across the different periods of Martian history is illustrated in Figure 1.

***1.2 Selection of a crater to demonstrate the Martian history and its fate***

Since impact craters are present from the early history of Mars, the oldest craters might have registered all the processes the planet has witnessed. But as time progressed, degradation and weathering altered the characteristics and morphologies of craters, especially the early and middle Noachian craters, hindering the study of sequential geologic and geomorphic processes. This can be exemplified through craters like Aram that eventually become chaotic terrain (Schumacher and Zegers, 2011). This observation forced us to choose the relatively well-preserved late Noachian craters as prime candidates to showcase the different processes on Mars. Through a prolific investigation of Robbins and Hynek (2012) database on Martian impact craters, we selected Morella Crater (Fig. 2a,b) as an apt candidate as it has witnessed several geologic and geomorphological processes. Morella Crater, a 76.97 km diameter complex crater, is nested with an extremely deep collapse structure, called Ganges Cavus, and is breached on its eastern side by Elaver Vallis outflow channel (Michalski, 2021). The crater manifest processes like crater burial (Fig. 2c), structural collapse (Fig. 2d), formation of outflow channel (Fig. 2e), paleolake formation, development of valley networks (Fig. 2f), aeolian activity (Fig. 2g), and late-stage impact events (Fig. 2h) in its most pristine form. Furthermore, Morella Crater provides an insight into the spectacular catastrophic floods that spawned on Mars by breaching its crater lake.

Thus, this detailed study envisages two aspects:

1. Showcasing the major planetary-scale geologic and geomorphic processes like cratering, volcanism, sepulchring, paleolake formation, breaching and outflow channel formation using Morella Crater as a proxy.
2. The odyssey from a fresh complex crater to a sepulchred crater narrating the fate of a Martian crater.

**2 Methodology**

***2.1 Interpreting the geomorphological features of Morella Crater***

The geomorphology of Morella Crater was thoroughly investigated using remotely sensed data products from various Mars missions such as Mars Global Surveyor (MGS), Mars Odyssey (MO), Mars Express (MEx), Mars Orbiter Camera (MOC), and Mars Reconnaissance Orbiter (MRO). Data were collected and organized using the JMARS, a software developed by the Arizona State University, and ArcGIS 10.8. The topographical analysis involved the above-mentioned multiple datasets along with MGS Mars Orbiter Laser Altimeter (MOLA) data combined with elevation data from the MEx High-Resolution Stereo Camera (HRSC). The composite MOLA and HRSC elevation data, with a grid size of 200 m/pixel, was employed to quantify topography whereas geomorphological evaluations were done using the visible and thermal infrared images of HRSC (10–20 m/pixel), CTX (~6 m/pixel), and HiRISE (~0.25 m/pixel).

***2.2 Delineation of Morella Basin***

As the study involves the evolution of the outflow channels of Morella Crater, the apt selection of the study area would be a drainage basin. The drainage basin along with the drainage network was delineated using ArcGIS 10.8 (www. desktop.arcgis.com/en/arcmap/). MOLA elevation data was used to delineate the drainage basin. Since the output is derived in a raster form, it is converted to polygons. Through stream order, frequency, and density of the basin, the morphometric parameters were delineated.

***2.3 Deciphering the morphometric characteristics of the transient Morella Crater***

Melosh's (1989) model suggests that the diameter of the transient crater (Dt) resulting from impacts on solid materials can be linked to the final diameter (D) (Eq. 1). The rim height (Hr) is attributed to a combination of structural uplift of nearby rocks and the deposition of ejecta from the crater (Grant et al., 2012) (Eq. 2).

|  |  |
| --- | --- |
| Dt = 0.84 D | …. (1) |
| Hr = 0.035 D1.014 | …. (2) |

The transient or apparent crater depth (d) is calculated using equation 3 (Garvin et al., 2000; Coleman et al., 2007)

|  |  |
| --- | --- |
| d = 0.19 D0.55 | …. (3) |

where D is the present-day rim diameter of the crater in km.

For estimating the transient excavation depths (de), equation 4 of Garvin et al. (2000) is used

|  |  |
| --- | --- |
| de = 0.131 Da0.85 | …. (4) |

where Da is the present-day rim diameter of the crater (km)

The central peak height (hcp) of Morella Crater is determined using equation 5 mentioned by Garvin et al. (2003)

|  |  |
| --- | --- |
| hcp=0.04 D0.51 | …. (5) |

where D is the diameter of the crater in km.

***2.4 Estimating the age of Morella Crater***

Morella Crater and its hinterland are evaluated for their crater chronology using the CSFD method (cf. Hartmann and Neukum, 2001). It involved several successive steps like fitting a production function, and ultimately estimating age using the chronology function. The current age calibration for Mars involves combining crater production data from Ivanov (2001) and the chronology function from Hartmann and Neukum (2001). CTX images (5–6 m/px) were utilized to enhance crater counts. Additionally, MOLA elevation data and hill shade (463 m/px) were employed to provide a broader regional context for each counting area. The ArcGIS extension Crater Tools was employed to execute crater counts. Finally, crater statistics and derivation of crater model ages were analysed using Craterstats software.

***2.5 Identifying the mineral assemblage in different morphological units***

Mineral identification was done using Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data. CRISM data analysis involves a series of steps using ENVI 5.3 software. Initially, the MTRDR cube file was downloaded (<https://pds-geosciences.wustl.edu/missions/mro/crism.htm>), and the details were extracted using IDL/ENVI. All the data are enhanced and accessed using CAT v6.5, a publicly released version of the software. The RGB band combinations are loaded with specified summary parameter combinations according to Viviano-Beck (2014). In Morella Crater, the HYD browse product corresponding R= SINDEX2, G= BD2100\_2 and B= BD1900\_2, and MAF browse product corresponding R= OLINDEX\_3, G= LCPINDEX\_2 and B= HCPINDEX\_2 was loaded. Then, the pixels with the strongest signals and pixels not highlighted in any of the summary parameters have been identified by taking the Z spectra from the scene. Browse products helps to identify the location of great potential for every scene. Spectral rationing is done by taking the end-member with the least noise as numerator s1 and end-member spectra extracted from the spectrally bland area as denominator s2. Different combinations of summary parameters are used to characterize different minerals like mafic minerals, hydrated sulfates, carbonated, hydroxylated silicates, ice content, and so on. The ratioed spectra obtained from the CRISM spectral imageries of the study area are then compared with the United States Geological Survey (USGS) laboratory reference spectra to locate the best mineralogy matches.

***2.6 Delineation of textural parameters of different regions of Morella Crater using THEMIS***

To delineate the textural parameters of Morella Crater, the study utilized high-resolution thermal inertia maps. These results were obtained from the observations of surface temperature on Mars by the Thermal Emission Spectrometer (TES) aboard the Mars Global Surveyor (MGS). The thermal inertia image mosaic utilized in this study is a quantitative (32-bit) mosaic generated from the Thermal Emission Imaging System (THEMIS) images captured during the 2001 MO orbiter mission. The mosaic was created using techniques outlined in Fergason et al. (2006). The mosaic spans the full spatial scale of the THEMIS infrared night time dataset, which is approximately 100 m/pixel.

***2.7 Modelling the catastrophic flood in Morella Crater using HEC-RAS***

Utilizing the HEC-RAS model, the hydraulic parameters of Morella crater and its hinterland have been simulated and studied to understand the massive floods and subsequent formation of outflow channels. The software employs diffusion wave equations for simulations. Modelling was run in clear water conditions. Steps to create a hydraulic model include establishing a coordinate project in the HEC RAS mapper, setting-up terrain using MOLA DEM and CTX imagery, defining 2D area boundaries, creating a computational mesh with Manning's values of 0.097 in the basaltic terrain of Morella, which is the value that corresponds to the terrestrial value 0.06 and converted by multiplying it with the square root of the ratio of terrestrial to Martian gravity (Burr, 2003), adding hydraulic structures and internal boundary conditions, setting external boundary conditions, inputting flow hydrographs and initializing the dam break analysis, configuring computation options for Martian conditions, and finally running the unsteady flow simulation. This presents a distinct opportunity to create a calibrated hydraulic model for a Martian flood within Morella crater.

***2.8 Reconstructing the morphology of Morella Crater using the Webgl-Erosion model***

To reconstruct the morphology of Morella crater as well as its temporal changes, an interactive erosion simulation was employed, utilizing the Lan lou/WebGl-Erosion platform available on GitHub (https://github.com/LanLou123/Webgl-Erosion). This erosion model was successfully used by Kakkassery et al. (2023) and Chandran et al. (2023). This platform acts as a comprehensive erosion simulator, modelling various aspects such as rivers, lakes, and terrain. Notably, it is a sophisticated computer model that emulates erosion and water flow, running directly within a web browser. Leveraging this interactive erosion simulation platform, Webgl-Erosion facilitates a detailed understanding of the surface modification process within the Morella crater. This was mainly used for recreating the morphology of Morella and its temporal changes, which was further used to represent a stage-wise model.

A flowchart of the entire methods adopted in this study is shown in figure 3 and the details of the datasets used in this study are shown in Supplementary Material 1.

**3 Results**

***3.1 Extent of the study area from drainage delineation***

To quantify the extent of the study area, especially in terrain etched with fluvial activity, the most feasible option is based on a drainage basin. Such practices of delineation of study areas are common in terrestrial conditions (cf. Akinwumiju et al., 2016). In this regard, the study also focused on the drainage basin encompassing Morella Crater as the study area. Similarly, the adjoining area was also examined to understand the morphometric characteristics and in turn, to correlate with Morella basin. Morella Basin, along with its neighbouring basins, is segmented into six distinct basins. Morella Basin covers an area of 5066.25 m2 and is larger as it was fed by a stream with 7th order. This 7th order stream originates from the SE of the study area and joins the outflow channel of the Morella Crater. Hence, this basin is further subdivided into two parts as the 7th order do not bear any relevance to the Morella Crater. This is labelled as (A) and (B), where (A) encompasses the Morella Crater and its outflow channels, and (B) occupies the rest of the basin. The correlation between Morella Crater and its neighbouring basins revealed lower drainage frequency and density in the basin that encompassed Morella Crater. Morella (A) has a drainage frequency of 0.075 and a drainage density of 0.082, while basin (B) has a frequency of 0.507 and a density of 0.131. In contrast, the remaining basins also have higher frequency and density values when compared to Morella A basin (Fig. 4a,b and Supplementary Material 2).

Top of Form

***3.2 Transient morphology of Morella Crater***

Based on equation (1), the transient crater diameter of Morella Crater is estimated at 64.65 km, and the initial rim height as per equation (2) is 2.86 km. Additionally, the transient crater depth calculated from equation (3) is 2.07 km and the transient excavation depth is determined as 5.26 km. Thus, Morella Crater is a complex crater, since the transition from simple crater to complex starts at 5 to 8 km on Mars (Pike, 1980); but in some cases, it is 9 to 12 km (Robbins and Hynek, 2012). The present diameter of the crater is 76.97 km. As Morella Crater is sepulchred, craters of similar diameter on Mars were also examined to understand the morphology underlying the buried surface. Consequently, a comparison was carried out on craters spanning a diameter range of 70 to 90 km, and around 429 craters were shortlisted from the database of Robbins and Hynek (2012). This analysis revealed that 76% of these craters were completely buried, 3% were partially buried, and the remaining 21% were pristine. The pristine craters exhibit various morphological features such as gullies, channels, dunes, and central elevated areas (CEA). For instance, the Ritchey crater with a diameter of 77.23 km is a relatively fresh complex crater characterized by terraced walls, a well-preserved rim, visible ejecta, and a CEA (Sun and Milliken, 2014). This CEA could potentially contain crustal materials exposed from depths as deep as 9.1 km (Caudill et al., 2012), prompting our interest in calculating the height of CEA of Morella Crater. Furthermore, almost all of the other analysed craters also exhibit a CEA. Thus, our results suggest the existence of a CEA for Morella Crater, and the central peak height of Morella Crater is determined as 0.37 km as per equation (5). A schematic sketch showing the transient morphology of Morella Crater is shown in Figure 5a.

***3.3 Geomorphological features of Morella Crater***

The crater experienced impact-induced volcanic activity, aeolian, tectonic, gravitational, lacustrine, and fluvial activities as well as impact-cratering events, wherein each process contributes to its unique geological and geomorphic overlay. Of the impact-induced volcanic activity, the most predominant was the burial of the crater. Based on the morphology of the crater (current depth of 1.16 km and an initial depth of 2.07 km), a lava flow of ~0.91 km in thickness might have accumulated within the crater. This lava flow should have been formed subsequent to the cratering as deep impact can produce a vast quality of melt (cf. Cassanelli and Head, 2016). Apart from the concealment of the crater by this melt, the geomorphic indicators of volcanic activity are relatively less prominent. Aeolian activities could be one of the significant ongoing activities within the crater since these are mostly responsible for burying the eastern plains of the crater meanwhile only the dunes are prominently visible in Ganges Cavus region. The connection between Morella Crater and the tectonic processes is established through the presence of faulting in the vicinity of Morella Crater. The dilational faulting by Ophir Catenae Structural Complex found across the surrounding area stands as a prominent piece of evidence pointing to the structural collapse within the crater that resulted in the formation of Ganges Cavus (Coleman, 2013). The gravitational processes in this crater are manifested in the walls of Ganges Cavus, particularly in the form of slope failures. Extensive signs of landslides are readily identifiable by the distinctive deposits left behind at the zone of accumulation (cf. Rajaneesh et al., 2022). The most notable geomorphic features within the crater are fluvial features, characterized by the presence of dark-toned channels on the crater plains. The morphology of these channels provides evidence of two distinct periods of water pooling within the crater. In the first period, crater infilling, followed by crater breaching and outflow channels, known as Elaver Vallis, were formed. This channel has produced a multitude of geomorphological features, including streamlined islands, hanging valleys, ridges, and grooves within Elaver Vallis. Based on its distinct morphological attributes, this outflow channel was divided into northern and southern channels by Coleman (2007). Surface degradation has led to the identification of patched chaos and chaotic terrain features within Elaver Vallis. The source of water could be those spouted from Ganges Cavus. In the second stage, valley networks were formed from the crater walls and flowed through the volcanic plains and debouched to the Ganges Cavus. As a result, dark-toned channels were formed on the plains of Morella. Both fluvial events led to the establishment of a paleolake wherein the first stage covered the entire crater whereas the second stage covered only the cavus region with little spill over. Additionally, the interior rim of Morella Crater exhibits a sequence of degraded terraces, possibly resulting from toe erosion associated with flooding (Goudge and Fassett, 2018). The geomorphic evidence of fluvial activity is further confirmed by studying two similarly sized craters within Morella Crater. Somerset is a well-preserved crater with a continuous rim, indicating relatively a new crater, probably formed after the lacustrine event in Morella Crater. On the other hand, Johnstown crater appears highly eroded with a degraded rim, suggesting that it predates the paleolake- conditions and is primarily filled by fluvial and lacustrine sediments. Even though these two are the prominent craters, there are numerous small impact craters within Morella Crater varying from pristine rayed craters to degraded craters. The different geomorphic features present in this crater are shown in Figure 5b.

***3.4 Mineral diversity on Morella Crater using CRISM data***

CRISM data significantly broadened our understanding of the mineral composition within Morella Crater. By analysing four MTRDR datasets, we gained valuable insights into the placement and distribution of minerals within the crater. CRISM imagery shows the presence of olivine and pyroxene on the western buried segments of Morella Crater (Fig. 6a,b), and augite, diopside and olivine on the eastern side. Olivine exhibited a broad absorption around 1 μm, and the broadness intensifies with higher Fe-content (Fig. 6d); while pyroxene, especially augite, showed characteristic absorptions near 1 μm and 2 μm. On the southern wall of the Ganges Cavus, hydrated minerals were identified, especially nontronite (Fig. 6c), while the northern wall of Morella Crater reveals the presence of olivine and augite. Nontronite, an iron-rich form of smectite, was identified by its characteristic absorption bands at 1.4 μm, 1.9 μm, 2.2 μm and 2.29 μm (Fig. 6d). The additional absorption band at 2.29 μm distinguishes nontronite from low-Fe smectites. Mafic mineral’s browse products highlight the prevalence of olivine and high-Ca pyroxene, denoted in red and blue/magenta, respectively, with low-Ca pyroxene in green/cyan on the floor of Morella Crater. Additionally, the hydrated mineral browse products within Ganges Cavus underscore the presence of hydrous minerals, as indicated by distinctive colours. The spectra were compared with those of the USGS spectral library (Fig. 6e).

***3.5 Textural parameters of Morella Crater materials***

The physical properties of surface materials on Morella Crater were analysed based on their response to temperature changes. Using THEMIS night-time images of the study area, textural features such as grain size (coarse or fine) and composition (rock or erosion particles) were determined (Fig. 7a). The crater plains are covered with materials exhibiting lower thermal inertia when compared to the surrounding rim. On the other hand, the light-toned unit in the NW and NE parts of the crater is composed of materials with higher thermal inertia. The crater plains also consist of regions with intermediate thermal inertia values. Areas with thermal inertia below 100 Jm−2K−1s−1/2 indicate the presence of loose, fine-grained materials like dust and sediments (Putzig et al., 2005). The eastern plains of Morella Crater exhibit these characteristics. Conversely, thermal inertia values exceeding 300 Jm−2K−1s−1/2 suggest a predominance of bedrock (Edwards et al., 2009), as manifested in the NW part of the rim. Clay mineral-bearing units, resembling light-toned and layered bedrock in visible images, possess thermal inertia values between 150 and 460 Jm−2K−1s−1/2 (Michalski and Fergason, 2009), confirming its composition, and are profusely seen in the cavus region. Similarly, olivine-enriched units were identified by thermal inertia values from 400 to 600 Jm−2K−1s−1/2 (Edwards et al., 2008) in the western plains of Morella Crater.

***3.6 Hydraulic parameters of a catastrophic flood in Morella Crater***

The collapse in the southern wall of Morella Crater that led to the formation of Ganges cavus might have exposed the permafrost layer. This eventually led to filling of the cavus, followed by paleo-lake formation in Morella Crater and culminating in the breaching of crater wall. The survival of liquid water throughout this process hinges on either of two factors: a consistently warm environment (cf. Farmer, 1976) or a local heat source, like faulting (cf. Coleman, 2013). This aspect is a subject of separate study, and hence, not elaborated here. In this study, we examined the outflows from Morella Crater using methods developed for analysing terrestrial dam failures and flooding, employing HEC RAS modelling. The breached rim of the crater confirmed that the water column exceeded 1750 m. This resulted in a catastrophic flood with a remarkable water surface elevation of 1873.66 m (Fig. 8a). MOLA elevation data was harnessed to precisely compute Morella Crater's volume, which is estimated at 4543.61 m3. The total volume of water involved in the flooding within Morella Crater was recorded at 2.50 x 1012 m3,and at the moment of crater breach, the water volume measured was 2.70 x 1012 m3. To illustrate the discharge rate, an advanced dam break analysis was employed, with the peak discharge falling within the range of 1.21 x 107 and 8.98 x 107 m3s-1 (Fig. 8b). Following the containment and breach of the crater walls, water rapidly drained, creating Elaver Vallis channels. Notably, of the two channels within this outflow channel, the southern channel exhibits consistently higher discharge rates at every station, while the northern channel maintains a relatively constant flow rate across all stations during the flood. The RAS Mapper interface, based on a 24-hour breach simulation period, showed that it took approximately 15.47 hours for the crater to breach. The initial water release from the cavus had a volume of 5.88 x 1010 m3. The cavus took around 8 hours to fill, reaching a maximum depth of 5013.51 m (Fig. 8c).

**4 Discussion**

Among the craters of different geological periods, the Hesperian craters on Mars are of particular interest because they maintain the original form similar to younger Amazonian craters while bypassing the severe denudation like the chaotic terrains found in the older Noachian craters. Out of the several craters that were scrutinized, we found Morella Crater as the potential candidate as it mirrored the diverse geological processes that have sculpted the Martian terrain. Based on our study, Morella Crater was described to undergo four distinct stages, tracing its journey from inception to its present state.

***4.1*** ***Sequels of major events at Morella Crater***

As mentioned, Morella Crater has been subjected to different geologic and geomorphic processes. For a stratigraphical understanding of these events, the chronological sequence must be deciphered. Based on the pristine nature of craters and the terrain in which they were etched, we have effectively determined the ages of four distinct terrains using the crater counting technique. By adopting the stratigraphic principles and through visual interpretation of different features within each age category, the processes were ordered to showcase the sequels of changes across the crater. Initially, the craters with pristine nature, other than the secondary craters, in the ejecta blanket of Morella Crater were dated. This yielded an age of approximately  Ga, placing the crater formation at late Noachian period (Fig. 9a,b). Secondly, the surface age of Morella Plains is estimated at  Ga, suggesting its formation during early Hesperian period (Fig. 9a,c). Craters in Elaver Vallis were estimated to be around Ga in age, indicating a late Hesparian/early Amazonian period (Fig. 9a,d). Furthermore, the age of dark-toned channels was estimated as Ga and it indicates an early Amazonian age. Based on the chronology, the entire processes can be clubbed into four different stages (Fig. 10), as detailed below.

***4.2 Stage 1: Origin of Morella Crater and its sepulchring***

Morella Crater was carved by a planetesimal impact onto a basaltic terrain. The transient morphometry of Morella Crater provides insights into the Martian conditions prevalent during late Noachian period. This study determined the key morphologic characteristics of Morella Crater, including its apparent depth, diameter, rim height, and the CEA. When comparing its transient and present states, the most notable difference is in the absence of CEA. This suggests that this area has undergone substantial burial due to impact-induced volcanic processes, in which a thick pile (~0.91 km) of lava/melt engulfed the crater. Lava formation is common in deep impact craters either due to the melting of impactites or the release of lava from the planetary interiors (Osinski et al., 2012). Thus, the CEA has been buried beneath the lava. The detection of olivine and pyroxene using CRISM data supports the volcanic origin of the material. Moreover, the relatively short temporal difference of 0.2 Ga between the crater's age and the formation of Morella Plain, implies that both processes occurred concurrently, and thus, the volcanic origin of plains could be the only viable process for the burial of the crater. But aeolian activity might also contributed to the sepulchring of the crater as the regions with low thermal inertia of <100 J m−2 K −1 s −1/2, especially on the eastern side of Morella Crater, confirm wind action. Thus, the crater was sepulchred through a combination of volcanic and aeolian activity, but dominated by the former. This stage demonstrates the formation of a large crater as well as volcanic and aeolian activity on Martian terrain.

***4.3 Stage 2: Large-scale subsidence and formation of Ganges Cavus***

Adjacent to the southern rim of Morella Crater, there is a 750 km long chain of pits extending from the eastern Candor Chasma to the western Ganges Chasma, known as Ophir Catenae Structural Complex (Coleman et al., 2007). This chain of pits represents a surface manifestation of a fault zone, indicating it was initially a graben system within the larger Valles Marineras Structural Complex (Coleman, 2013). This fault system might have provided sufficient heat source to melt the permafrost region within Morella Crater (Komatsu et al., 2009). The melting of huge quantities of ice in this region might have triggered subsidence to create Ganges Cavus. This depression, combined with the fault system, likely pressurized the adjacent aquifer system to pool water in the cavus. The time of formation of this cavus is constrained between  Ga (burial of Morella Crater) and around  Ga (age of formation of Elaver Vallis). This age concurs with the time of formation of Ophir Catenae Structural Complex (cf. Marra et al., 2015), which is of early to late Hesperian. This shows that the probable mechanism of the formation of Ganges Cavus is the faulting associated with Ophir Catenae Structural Ccomplex.

***4.4 Stage 3: Flooding of Ganges Cavus and Morella Crater***

Clifford and Parker (2001) theoretically estimated the depth of the equatorial cryosphere on Mars and suggested it to range between 2.3 and 11 km. Ganges Cavus is approximately 5 km deep and it matches with the depth parameter required to encounter the cryosphere. The continued supply of heat from Ophir Catenae Structural Complex might have melted more permafrost regions across Ganges Cavus. The formation of this cavus also triggered the surrounding pressurized aquifers to pool water in the cavus. As there are no inlets into Morella Crater, the only possible source of water is expected within the crater premises itself. The substantial outburst of groundwater created a catastrophic pooling in Morella Crater. Eventually, the lake level rose until the wall of Morella Crater was overtopped and breached, leading to a catastrophic release of ponded water and the carving of Elaver Vallis Channel Complex. CRISM imaging reveals the presence of nontronite, a hydrous mineral, in the southern wall of Ganges Cavus, which is formed by hydrothermal action (Gates et al., 2002). This location of Ganges Cavus where nontronite is reported is the site of interception of Ophir Catenae Structural Complex with this cavus. Thus, the source linked to the supply of heat is obvious. In contrast, the northern wall of this cavus displays mafic minerals such as olivine and pyroxene, which forms a part of the lava floor.

The presence of dark-toned channels in Morella Plain suggests a second stage of flooding, probably after a long hiatus. The source water could be from the walls of the inner crater rim. The runoff from the centripetal drainages originating from the elevated rim of the crater (cf. Indu et al. 2022) might have eroded the duricrust layer of the plain dominated by olivine and eventually exposed the underlying pyroxene-rich zones, giving a dark appearance to the fluvial network. This water filled the cavus, but not the crater and this was revealed by the flood marks, manifested as dark tones, seen around the cavus.

***4.5 Stage 4: Formation of Elaver Vallis***

The surface of Morella Crater has a gradual decrease in slope from west to east, facilitating the creation of water pressure on the eastern side of the crater rim, which eventually breached, and resulted in the formation of Elaver Vallis outflow channels during the first stage of flooding. These outflow channels provide an extensive opportunity to study catastrophic floods that spawned from a breached crater. While utilizing the crater counting techniques, the age of Elaver Vallis align with late Hesperian/early Amazonian period. The channel's features closely resemble those of mega-flood formations, such as channel topography, streamlined islands, grooves, ridges, and hanging valleys. The post-flood degradation in the region results in patchy chaos and chaotic terrains. Moreover, Elaver Vallis is divided into northern and southern channels, the northern channel exhibits higher flow velocity and water volume. This flooding and breaching have created a massive release of water with a volume of 2.50 × 1012 m3 and the peak discharge rate within the range of 1.21 × 107 m3s-1 and 8.98 × 107 m3s-1, which is similar to the Luray flood in the Altai Mountains of south-central Siberia from an ice dam failure (water volume of 1012 m3 and the peak discharge rate of 107 m3s-1) (cf. Baker et al., 1993; Komatsu et al., 2009). Furthermore, the derived hydraulic parameters concur with the results of Coleman (2013. Elaver Vallis terminates abruptly at the southern rim of Ganges Chasma.

**5 Conclusion**

The findings of this study yielded significant insights into the entire history of Morella Crater, which exemplifies the fate of a Martian impact crater. In brief, this study can be outlined as follows:

i. The transient morphology of Morella Crater reveals the typical features of a complex crater with a CEA.

ii. Concomitant to its formation, the crater was flooded with basaltic lava that sepulchred the crater. Although minimal, aeolian activity also contributed to sepulchring.

iii. The heat from Ophir Catenae Structural Complex melted the permafrost, which later created Ganges Cavus through a deep subsidence. This heat also hydrothermally altered the lithological units and deposited nontronite, a hydrous mineral.

iv. Subsequently, the breakout of confined groundwater created a paleo-lake in Morella Crater.

v. The lake level rose until the wall of Morella Crater was overtopped and breached, leading to the catastrophic release of ponded waters and the carving of Elaver Vallis Channel Complex.

vi. Elaver Vallis outflow channel denuded and created patchy chaotic terrains.

vii. All the above sequel narrates the fate of a Martian crater.

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**Data Availability Statement**

The collection of data used in this research was from MGS MOLA DEM, MRO HiRISE, MRO CTX, MO THEMIS, and MRO CRISM can be downloaded from the NASA Planetary Data System (PDS) (Malin et al., 2007, McEwen et al., 2007, Christensen et al., 2003, Murchie et al., 2007).

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Fig. 1 Bar diagram outlining the significant geologic and geomorphic processes on the Martian terrain since its origin (Sourced from different literature and mentioned in appropriate locations in the text).

Fig. 2 Location map of Morella Crater on (a) Mars (Source: J MARS) (b) Elevation map of study area draped over hill shade (Source: MOLA DEM). The crater undergoes a sequence of various processes, which are chronologically represented as (c) Buried crater (Source: MOLA DEM) (d) collapse/subsidence leading to the formation of Ganges Cavus (Source: Google Mars) (e) Valley networks (HRSC image) (f) outflow channels of Elaver Vallis formed by the breaching of Morella Crater, impregnated with contours (MOLA DEM)(g) Dunes indicating the aeolian activity (HRSC image) (h)later impact events in Morella Crater (Source: HiRISE image)

Fig. 3 Schematic outlines of the study's methodology, encompassing data sources, software, and results.

Fig. 4 Automated drainage and basin extraction of Morella Crater and its hinterland (a) adjacent basins and (b) Morella Basin (Source: MOLA DEM)

Fig. 5 (a) Webgl-derived schematic model depicting the transient morphometry of Morella Crater. Transient diameter, depth, rim height, and central elevated area are shown (b) distinctive geomorphic features within Morella Crater and Elaver Vallis. Terraces, channels, grooves, mounds, dunes, and slope instability features as well as two major craters: Somerset (S) and Johnstown (J). The crater connects to Elaver Vallis through a spillway, where it displays hanging valleys, grooves, ridges, streamlined islands, chaotic terrain, and chaos (Source: Themis daytime image)

Fig. 6 CRISM and laboratory reflectance spectra illustrating the mineral diversity at Morella Crater (a) available CRISM data products of the study area (b) browse products in Morella lains, highlighting mafic minerals (c) browse products in the study area, emphasizing hydrous minerals (d) CRISM ratioed reflectance spectra of nontronite, olivine, and pyroxene (e) Stacked laboratory reflected spectra of olivine, nontronite, and pyroxene.

Fig. 7 THEMIS infrared map of Morella Crater: (a) A mosaic of THEMIS night-time images of Morella (b) Cross-sectional profile of thermal inertia map showing the distinction between olivine and pyroxene dominated areas. An elevation profile is also shown, which manifests the dark-toned channels.

Fig. 8 The calibrated catastrophic flood hydraulics of Morella Crater (a) water surface elevation of the flood superimposed on a CTX image (b) flow velocity of the catastrophic flood (c) Inundation depth map of Morella.

Fig. 9 Crater size-frequency distributions and the ages of formation of Morella Crater, the Morella Plains, and Elaver Vallis (a) craters used for counting are shown on the CTX mosaicked image. Yellow circles mark craters outside Morella Crater, red circles indicate craters within Morella Plains, and blue circles represent those within Elaver Vallis (b) CSFDs and derived model ages for Morella Crater (c) Correspond to the CSFDs and derived model ages of the interior of Morella Plains (d) CSFDs and derived model ages of Elaver Vallis.

Fig. 10 Schematic sketches showing the evolutionary history of Morella Crater: (a) Morella in its transient form with a characteristic CEA (b) Over time, the crater becomes buried and acquires its sepulchral appearance (c) Formation of the collapsed structure, Ganges Cavus, which was formed subsequent to the rupture in the cryosphere (d) Water begins to emerge from Ganges Cavus (e) Eventual pooling of the crater (f) Final crater breach in the eastern rim, giving rise to outflow channels.

**List of Supplementary Tables**

1. Details of the datasets used in this study
2. Morphometric analysis of the different basins of Morella Crater and its hinterland